

# Influence of epithermal muonic molecule formation on kinetics of the $\mu\text{CF}$ processes in deuterium

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## Abstract

The non-resonant formation of  $dd\mu$  molecules in the loosely bound state in collisions of non-thermalized  $d\mu$  atoms with deuterium molecules  $\text{D}_2$  has been considered. The process of such a type is possible only for collision energies exceeded the ionization potential of  $\text{D}_2$ . The calculated rates of  $dd\mu$  formation in the above-threshold energy region are about one order of magnitude higher than obtained earlier.

The role of epithermal non-resonant  $\mu$ -molecule formation for the kinetics of  $\mu\text{CF}$  processes in  $\text{D}_2$  gas was studied. It was shown that the non-resonant  $dd\mu$  formation by  $d\mu$  atoms accelerated during the cascade can be directly observed in the neutron time spectra at very short initial times.

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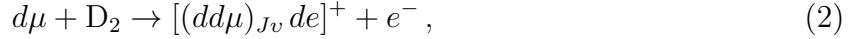
## I. INTRODUCTION

The studies of various reactions with negative  $\mu^-$  muons in a deuterium target and the muon catalyzed fusion ( $\mu$ CF) phenomenon in particular give rise to special interest in the  $dd\mu$ -molecule-formation processes (see works [1, 2] and references therein). In collisions of the  $d\mu$  atoms with the deuterium  $D_2$  molecules, the  $dd\mu$  molecules are formed in one of the five bound states, which are defined by the different rotational ( $J$ ) and vibrational ( $v$ ) quantum numbers [3]. The loosely bound state with binding energy  $|\varepsilon_{J=1,v=1}| = 1.975$  eV refers to  $dd\mu$  formation by the resonant reaction:



where the released energy  $\varepsilon \approx 2$  eV is transferred to the excitation of ro-vibronic ( $K\nu$ ) states of the molecular complex  $[(dd\mu)dee]$ , according to the resonance mechanism [4]. At the temperature conditions of the majority of previous experiments, the processes (1) mainly occur for thermalized  $d\mu$  atoms in the ground state. The rate  $\lambda_{dd\mu}$  of resonance reaction (1) depends on the target temperature  $T$  and is on the order of  $10^6$  s $^{-1}$  [2, 5] for room temperature  $T = 300$  K.

In any other ( $Jv$ ) state, the  $dd\mu$  molecules are formed via the non-resonant process (2):



with conversion of the released energy into electron ionization of the  $D_2$  molecule (see references in reviews [1]). The rates of transitions to all existing  $dd\mu$  ro-vibronic states have been calculated in [6]. It has been shown that collisions of the thermalized  $d\mu$  atoms with the  $D_2$  molecules lead to non-resonant formation of  $dd\mu$  molecules with the rates  $\lambda_{dd\mu} \sim 10^4$  s $^{-1}$ , whereas these rates are on the order of  $10^6$  s $^{-1}$  for non-thermalized  $d\mu$ 's.

It should be noted that for thermalized  $d\mu$  atoms the non-resonant  $dd\mu$  formation (1) in the state  $J = v = 1$  is impossible. However, as presented in this work, such a process is realized for the non-thermalized  $d\mu$  atoms. Also, it is shown that the calculated non-resonant rates are much higher than the data obtained in Ref. [6].

## II. NON-RESONANT FORMATION OF $dd\mu$ MOLECULE

For thermalized  $d\mu$  atoms, collision energies  $\varepsilon$  are usually much less than the ionization potential  $I_e = 15.46$  eV of the  $D_2$  molecule ( $\varepsilon \ll I_e$ ). Then the non-resonant  $dd\mu$  formation (2) in the loosely bound state with electron conversion is impossible ( $\varepsilon_{11} < I_e$ ), and only resonant formation (1) is realized. However, the reactions (2) take place for  $dd\mu$  formation in deeper bound states with binding energies  $\varepsilon_{Jv} \geq I_e$ . Besides, when the non-thermalized  $d\mu$  atoms have quite high energies  $\varepsilon \geq I_e$ , the non-resonant formation of  $dd\mu$  molecules in the loosely bound state ( $J = 1, v = 1$ ) also becomes possible.

A method for calculating the non-resonant formation rates in collisions of the epithermal  $d\mu$  atoms with the  $D_2$  molecules is analogous to the method developed in Ref. [6]. There it was shown that the dominating transitions from the scattering states of the  $d\mu + d$  system to the bound states of muonic molecules, with the total orbital angular momenta  $J = 1$ , are the electric  $E1$  transitions only. Such transitions have been considered in this work. The corresponding rates are presented in Fig. 1a as functions of collision energy  $\varepsilon$  in the center of mass of the system  $d\mu + D_2$  (additionally, the analogous dependencies of non-resonant

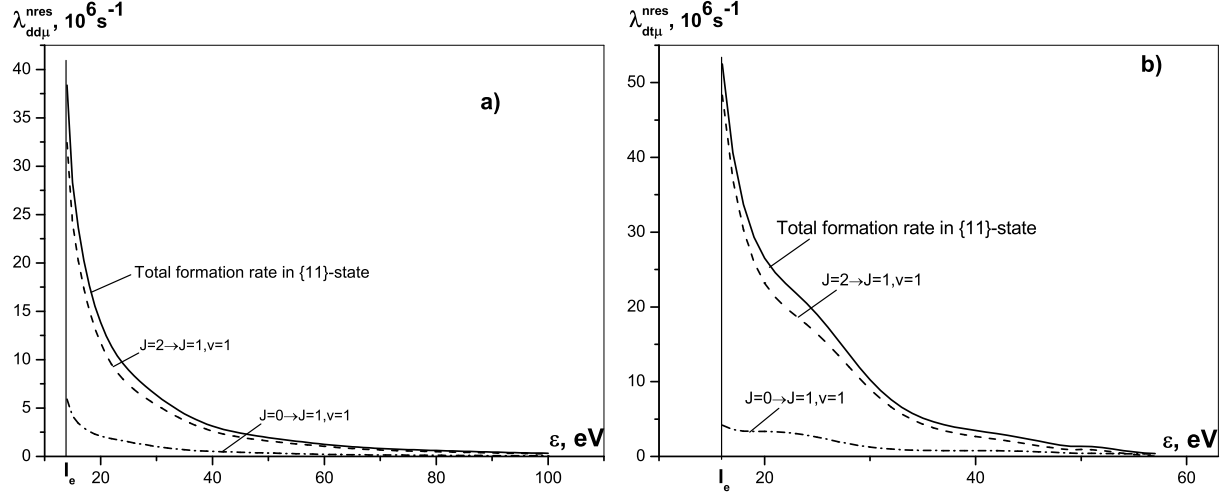


FIG. 1: Non-resonant formation rates of  $dd\mu$  (a) and  $dt\mu$  (b) in the state ( $J=v=1$ ). The dash-dotted and dashed lines denote the  $E1$ -transitions from the initial states  $J = 0$  and  $J = 2$ , respectively.

formation rates of the  $dt\mu$  molecules are shown in the Fig. 1b). At  $\varepsilon = I_e - |\varepsilon_{11}|$ , the plotted rates have a typical threshold peculiarity and maximum values, because of the existence of the loosely bound state (11).

In Fig. 2, the obtained results are compared with the earlier calculated total rates of non-resonant  $dd\mu$  formation [6] in the rotational states  $J = 1$  and  $J = 0$ , as well as resonant formation in the ( $J = 1, v = 1$ ) state [7]. It is apparent that in the above-threshold energy

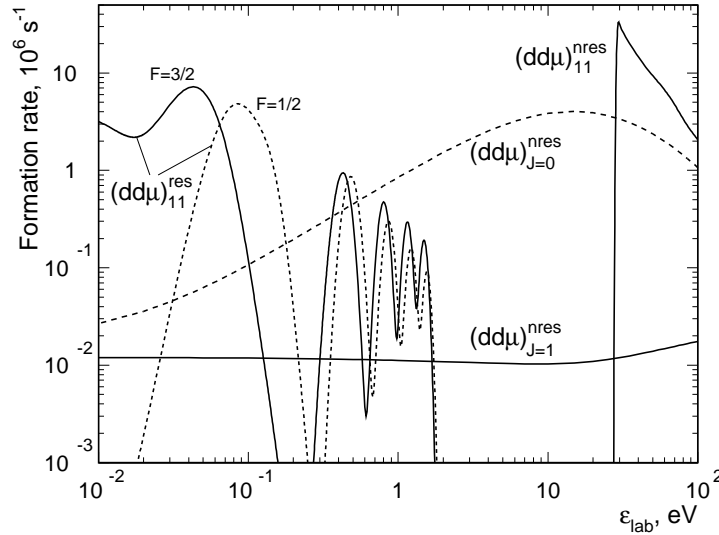


FIG. 2: Resonant and non-resonant  $dd\mu$  formation rates versus  $d\mu$  kinetic energy in laboratory system.

region the calculated rates of  $dd\mu$  formation in the loosely bound (11) state are about one order of magnitude higher than the rates [6] of  $dd\mu$  formation in the lower state  $J = 0$ . Also, they are more than three orders of magnitude higher for formation in the  $J = 1$  ( $v \neq 1$ ) state. This follows from the fact that the overlap of the wave functions of the initial and

final states of the  $d\mu + D_2$  system is much stronger in the case of non-resonant  $dd\mu$  formation in the loosely bound ( $J = 1, v = 1$ ) state than in the state ( $J = 1, v \neq 1$ ).

### III. DEMONSTRATION OF THE EPITHERMAL $dd\mu$ FORMATION EFFECT

The kinetics of  $\mu CF$  processes in a pure  $D_2$  gas has been studied in order to take into account effects of the presence of non-thermalized  $d\mu$  atoms. For this purpose, the kinetic-energy distributions of  $d\mu$  atoms in different atomic states, which are established just after cascade de-excitations of the formed  $d\mu$ 's, have been calculated using method [8]. These calculations confirmed that most of the  $d\mu$  atoms in the final  $1S$  state are not thermalized, due to collisions in the cascade process [9, 10]. For simplicity of further numerous calculations, an assumption of a simple two-Maxwell shape of the initial energy distribution of  $d\mu$  atoms [7, 9] has been employed. One of the Maxwell components of this distribution corresponds to the non-thermalized atoms, while the second component describes the thermalized atoms. The time spectra of neutrons from the  $dd$  fusion in  $dd\mu$  have been calculated by means of Monte-Carlo simulations of the kinetics of  $\mu CF$  processes [7]. They are shown in Figs. 3a,b for the  $D_2$ -gas target at temperature  $T=40$  K and density  $\phi=0.05$  (in the liquid-hydrogen-density units). Since the accuracy of calculating the kinetic-energy distribution of  $1S$   $d\mu$  atoms is still insufficient, the two average energies  $\varepsilon_{\text{avg}} = 10$  eV (Fig. 3a) and  $\varepsilon_{\text{avg}} = 50$  eV (Fig. 3b) of the non-thermalized Maxwell component [7] have been chosen. The neutron spectra with both the resonant and non-resonant  $dd\mu$  formation taken into account are represented by the solid lines, while the dashed lines have been calculated without the presence of the non-resonant formation processes.

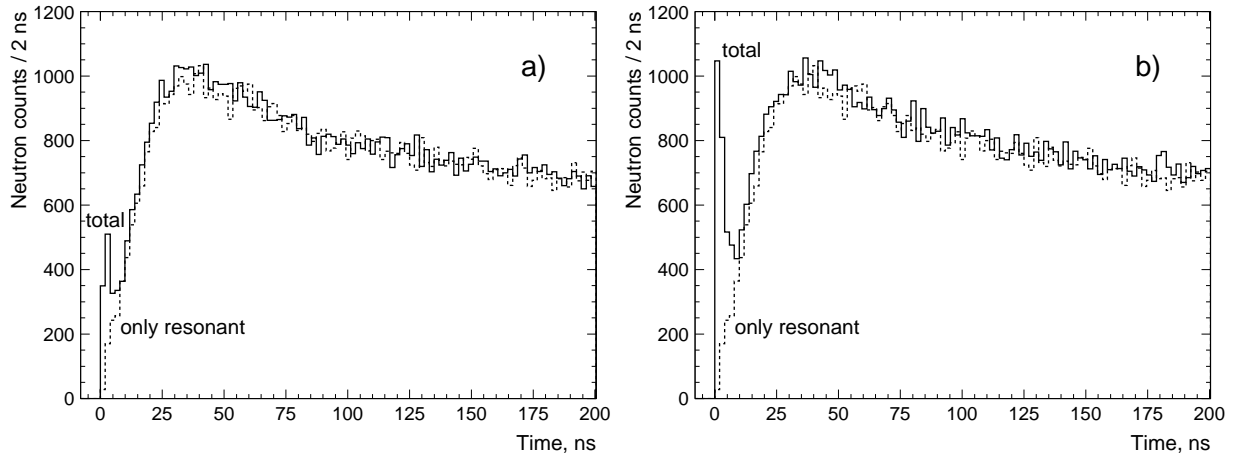


FIG. 3: Neutron spectra from  $dd$  fusion in  $D_2$  at  $T = 40$  K and  $\phi = 0.05$  (solid line) and the analogous spectrum obtained assuming absence of nonresonant  $dd\mu$  formation (dashed line): a) the initial mean energy of non-thermalized  $d\mu$  atoms  $\varepsilon_{\text{avg}} = 10$  eV, b)  $\varepsilon_{\text{avg}} = 50$  eV.

The significant effect of the epithermal non-resonant  $dd\mu$  formation is displayed in Fig. 3 as a peak at the time  $t \approx 5$  ns. According to Fig. 2, it is clear that such an effect can be revealed only at short times ( $t \lesssim 20$  ns), when most of the  $d\mu$  atoms are not yet slowed down to the energy region corresponding to the high peaks of resonant formation. In Fig. 3b, the prompt peak is more pronounced since the non-thermalized fraction of initial  $d\mu$ 's corresponds to a higher mean energy  $\varepsilon_{\text{avg}} = 50$  eV.

The enhancement of the neutron yield from  $dd$  fusion at short times, which was already observed in  $\mu$ CF experiments in  $D_2$  gas (Fig. 11 in Ref. [2]) and was even more pronounced in HD gas (Fig. 18 in Ref. [2]), confirms the nature of phenomenon considered above. A further consistent comparison between the measured and calculated neutron time spectra for the  $\mu$ CF in  $D_2$  target would enable drawing a final conclusion about the mean energy of  $d\mu$  atoms in the  $1S$  state, which are accelerated in the cascade processes.

#### IV. CONCLUSIONS

A study of the kinetics of  $\mu$ CF processes in  $D_2$  gas, in particular the neutron spectra at short times, revealed the significant role of the non-resonant formation of  $dd\mu$  molecules at kinetic energies characteristic to the non-thermalized ground-state  $d\mu$  atoms, which are accelerated during the atomic cascade.

Besides the well-known processes (1) and (2) of  $\mu$ -molecule formation, a new possibility of non-resonant formation of the  $dd\mu$  molecule in the loosely bound state in the presence of non-thermalized  $d\mu$ -atoms has been considered. The calculated rates of such formation reach the magnitude  $\lambda_{dd\mu} \sim 10^6 \text{ s}^{-1}$ , near the energy threshold of reaction (2). Therefore, these reactions should also be taken into account in analyses of  $\mu$ CF kinetics in deuterium, in particular, at low target densities. Moreover, detailed information on the experimental short-time neutron spectra would allow to extract the mean energy of  $d\mu$  atoms in the ground state and to estimate the reliability of various cascade-characteristics calculations.

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